Holocene debris flows on the Colorado Plateau: The influence of clay mineralogy and chemistry

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ABSTRACT

Holocene debris flows do not occur uniformly on the Colorado Plateau province of North America. Debris flows occur in specific areas of the plateau, resulting in general from the combination of steep topography, intense convective precipitation, abundant poorly sorted material not stabilized by vegetation, and the exposure of certain fine-grained bedrock units in cliffs or in colluvium beneath those cliffs. In Grand and Cataract Canyons, fine-grained bedrock that produces debris flows contains primarily single-layer clays—notably illite and kaolinite—and has low multilayer clay content. This clay-mineral suite also occurs in the colluvium that produces debris flows as well as in debris-flow deposits, although unconsolidated deposits have less illite than the source bedrock. We investigate the relation between the clay mineralogy and major-cation chemistry of fine-grained bedrock units and the occurrence of debris flows on the entire Colorado Plateau. We determined that 85 mapped fine-grained bedrock units potentially could produce debris flows, and we analyzed clay mineralogy and major-cation concentration of 52 of the most widely distributed units, particularly those exposed in steep topography. Fine-grained bedrock units that produce debris flows contained an average of 71% kaolinite and illite and 5% montmorillonite and have a higher concentration of potassium and magnesium than nonproducing units, which have an average of 51% montmorillonite and a higher concentration of sodium. We used multivariate statistics to discriminate fine-grained bedrock units with the potential to produce debris flows, and we used digital-elevation models and mapped distribution of debris-flow producing units to derive a map that predicts potential occurrence of Holocene debris flows on the Colorado Plateau.

Keywords: debris flow, mass wasting, geomorphology, Colorado Plateau, sedimentary rock, clay mineralogy, major-cation chemistry.

INTRODUCTION

Debris flows occur in numerous small drainages on the Colorado Plateau (Fig. 1) of the southwestern United States (Woolley, 1946; Radbrunch-Hall et al., 1976; Cooley et al., 1977; Hereford et al., 1998; Elliott and Hammack, 1999; Brabb et al., 1999; Griffiths et al., 2004; Webb et al., 2004) and in adjacent arid and semiarid regions (Blackwelder, 1928; Hammack and Wohl, 1996; Larsen et al., 2004). These debris flows most commonly initiate as shallow slope failures in either fine-grained bedrock units or colluvial deposits that accumulate beneath those units (Fig. 2). Deep-seated landslides that mobilized into debris flows occurred on the Colorado Plateau in the Pleistocene (Williams, 1984), but in this paper we limit our discussion to Holocene debris flows that can travel long distances (>1 km) from source to site of deposition (Cooley et al., 1977; Griffiths et al., 2004; Webb et al., 2004).

Holocene debris flows initiate on steep slopes in response to intense or prolonged precipitation, but those factors alone do not explain where debris flows occur on the Colorado Plateau. In Grand Canyon, where debris flows have received the most intensive study (Webb et al., 1988, 2000; Griffiths et al., 2004), debris flows that travel long distances have a matrix with a distinctive mineralogical suite comprised mostly of single-layer clays such as illite and kaolinite and a less distinctive, major-cation content generally low in sodium (Griffiths, 1995). Others (Hampton, 1975; Pierson and Costa, 1987) have proposed that major-cation chemistry may affect debris-flow transport.

We hypothesize that the occurrence of debris flows on the Colorado Plateau can be at least partially explained by a correspondence of steep slopes and fine-grained sedimentary rocks containing illite and kaolinite and with a low sodium content. In this paper, we compare the clay fractions of fine-grained bedrock units, the colluvium that these units produce, and associated debris-flow deposits to determine if clay mineralogy and major-cation chemistry of those materials are similar. We classify fine-grained bedrock units in terms of debris-flow potential on the basis of field observations of failure points on steep slopes and whether or not there are associated Holocene debris-flow deposits, and we determine if these units can be statistically segregated into debris-flow producers and nonproducers on the basis of clay mineralogy and major-cation chemistry. We use the spatial distribution of steep slopes and outcroppings of these units to create a map of the potential for Holocene debris flows on the Colorado Plateau.

BACKGROUND

Setting

Comprising more than 300,000 km^2 (Fig. 1), the Colorado Plateau is distinguished from other physiographic provinces in North America by its unique geologic structure, stratigraphy, elevation, and steep-walled canyons (Hunt, 1967). The Plateau has a relatively high elevation, averaging 1900 m. Tectonically, it is relatively

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stable, especially in comparison to the adjacent Basin and Range and Rocky Mountain provinces. It is bounded on the west by the Wasatch Line (Baars, 2000), a series of normal faults (the Sevier Fault, Hurricane Fault, and Grand Wash Fault) extending south from the Wasatch Fault in northern Utah. Earthquakes along this margin have triggered historical landslides (Jibson and Harp, 1996). On its southern margin, the Colorado Plateau is separated from the Basin and Range province by the Mogollon Rim; in the southeast, it is bounded by the Rio Grande Rift; and to the east, northeast, and north, the Rocky and San Juan mountain ranges form the margin. The geologic strata of the Colorado Plateau generally are flat lying, although several structural flexures—such as the Piceance, San Juan, Uinta, and Navajo basins and the Kaibab, Defiance, Zuni, Uncompahgre, San Rafael Swell, and Circle Cliffs upwarps—contribute to locally high relief.

Holocene debris flows in this region are initiated from shallow-seated failures of limited spatial extent on steep slopes during intense rainfall. Debris flows that are mobilized from larger-scale, deep-seated landslides (Iverson et al., 1997) are rare under Holocene climatic conditions on the Colorado Plateau, although such debris flows have occurred at specific sites on or adjacent to the Plateau (Williams, 1984; Boison and Patton, 1985; Brabb et al., 1989). Most Holocene debris flows are related to: (1) steep topography, particularly along river canyons with relief of greater than 1000 m; (2) intense rainfall, particularly summer convective thunderstorms; and (3) abundant poorly sorted sediment, particularly in unconsolidated fine-grained bedrock or colluvium developed from such bedrock (Webb et al., 1989; Griffiths et al., 2004; Webb et al., 2004).

Influence of Topography

On the Colorado Plateau, debris flows are most common along the Colorado River and its major tributaries where steep terrain, and particularly vertical cliffs, line the river corridors. Of 600 mass-wasting events in Utah cataloged by Schroder (1971), the greatest number, including most debris flows, occurred in high-relief canyon settings, underscoring the importance of steep terrain along the Colorado River and its principal tributaries (Figs. 2 and 3). Canyon walls can exceed 1500 m in height, most famously in Grand Canyon, where relatively flat-lying limestone, sandstone, and fine-grained bedrock units are exposed and largely unvegetated (Fig. 2A). Our observations in Grand Canyon indicate that the minimum slope required for debris-flow initiation is ~20°.

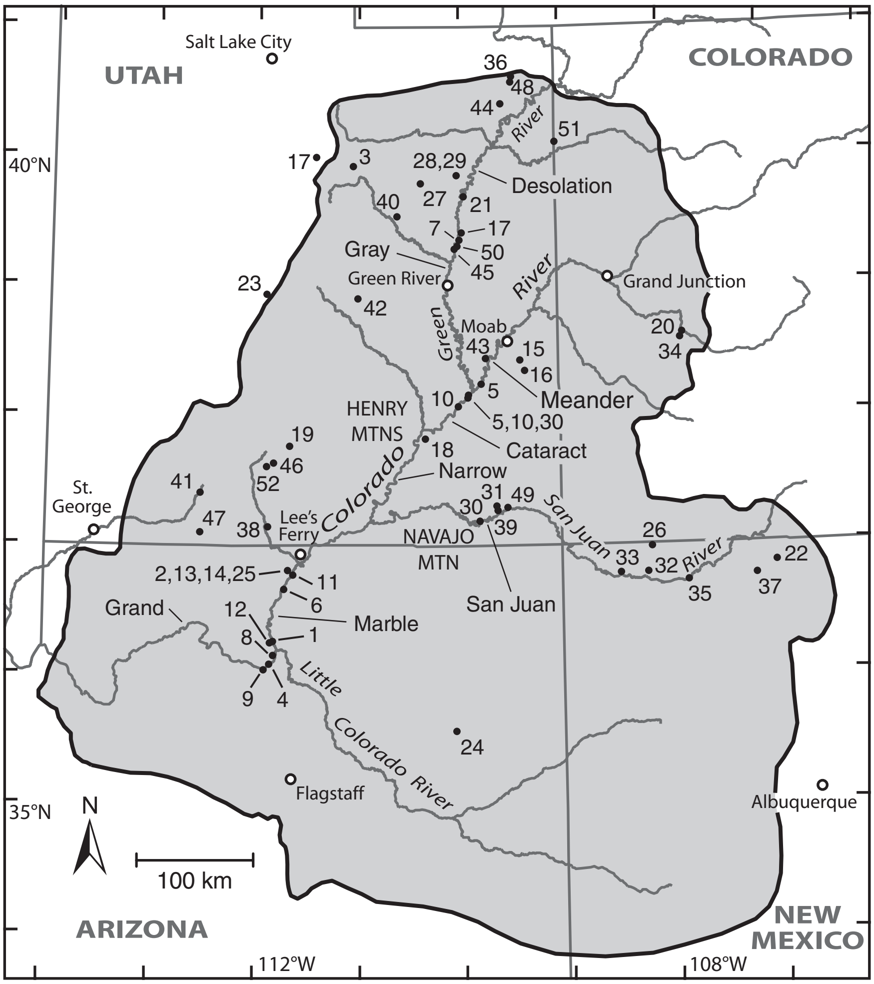


Figure 1. The Colorado Plateau physiographic province (Hunt, 1967) showing the major tributary and mainstem reaches of the Colorado River and the locations of samples collected from fine-grained bedrock for analysis of clay mineralogy and major-cation concentrations. Mon.—Monitor; Br.—Brushy; SS/LS—Sandstone/Limestone.

Debris flows can occur well away from river corridors, particularly in laccolithic ranges, such as Navajo Mountain and the Henry Mountains (Fig. 1), where conical relief spawns debris flows (Hanks et al., 2002; Garvin et al., 2005). Many cliffs, such as the Book Cliffs near Green River, Utah, are associated with differential erosion of shales versus more resistant sandstones or limestones and, despite their impressive relief, many of these cliffs do not produce debris flows. Geologic hazard maps of the region (e.g., Brabb et al., 1989) show that debris-flow occurrence is coincident with steep terrain, generally on slopes greater than ~20°. Steep terrain alone is insufficient to produce debris flows in this region. For example, debris flows rarely or do not occur along the Book Cliffs and in the steep-walled canyons of the San Juan River (Fig. 3), suggesting that other factors are also important to determining where debris flows occur on the Colorado Plateau.

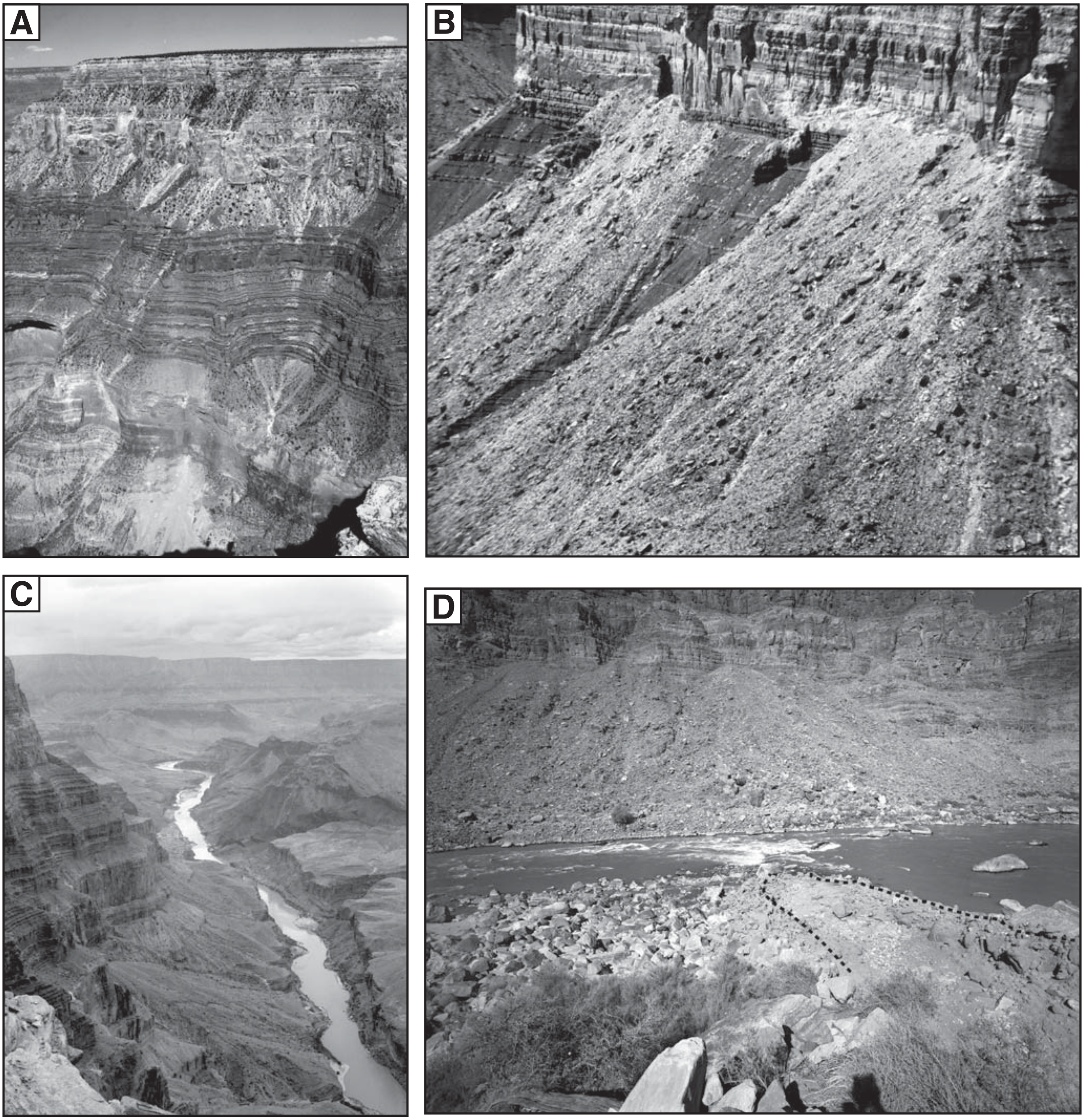


Figure 2. (A) Upper Paleozoic bedrock in Grand Canyon. The prominent dark-banded sediment in the middle of the view is the Supai Group (Pennsylvanian-Permian). Debris flows in Grand Canyon commonly initiate during failures in the slope-forming units of the Supai Group as well as the overlying Hermit Formation (Permian) (Webb et al., 1988), shown in this view with a mottled colluvial cover. (B) Colluvium overlying the Hermit Formation in Grand Canyon. The cliff-forming unit at top is the Coconino Sandstone (Permian). Debris flows commonly initiate either by streamflow coursing over the vertical cliffs or by undercutting along steep channel edges (Melis et al., 1994). (C) Downstream view of the Colorado River corridor in Grand Canyon from Cape Solitude. Prominent colluvial deposits mantle the slopes of Cambrian Tapeats Sandstone in the midground. The broken pyramid in the center midground is mostly Proterozoic Cardenas Lavas. Debris flows in this reach commonly initiate by the firehose effect of waterfalls impinging on colluvium (Melis et al., 1994). (D) View down a steep slope showing paired levees (right center) of a 1999 debris flow (designated with dashed lines) and older levees along an unnamed channel leading into the head of Rapid 15, Cataract Canyon. The fresh debris-flow deposits are red, reflecting the clay minerals contributed by the Halgaito Formation (Permian), the main source of fine-grained sediment for debris flows in Cataract Canyon (Webb et al., 2004). The colluvial deposits across the river mantle slopes underlain by Honaker Trail Formation (Pennsylvanian), which, with the Cedar Mesa Sandstone (Permian; not shown), are the primary sources of coarse sediment in colluvium and debris-flow deposits. (Photographs courtesy of the Desert Laboratory Collection of Repeat Photography.)

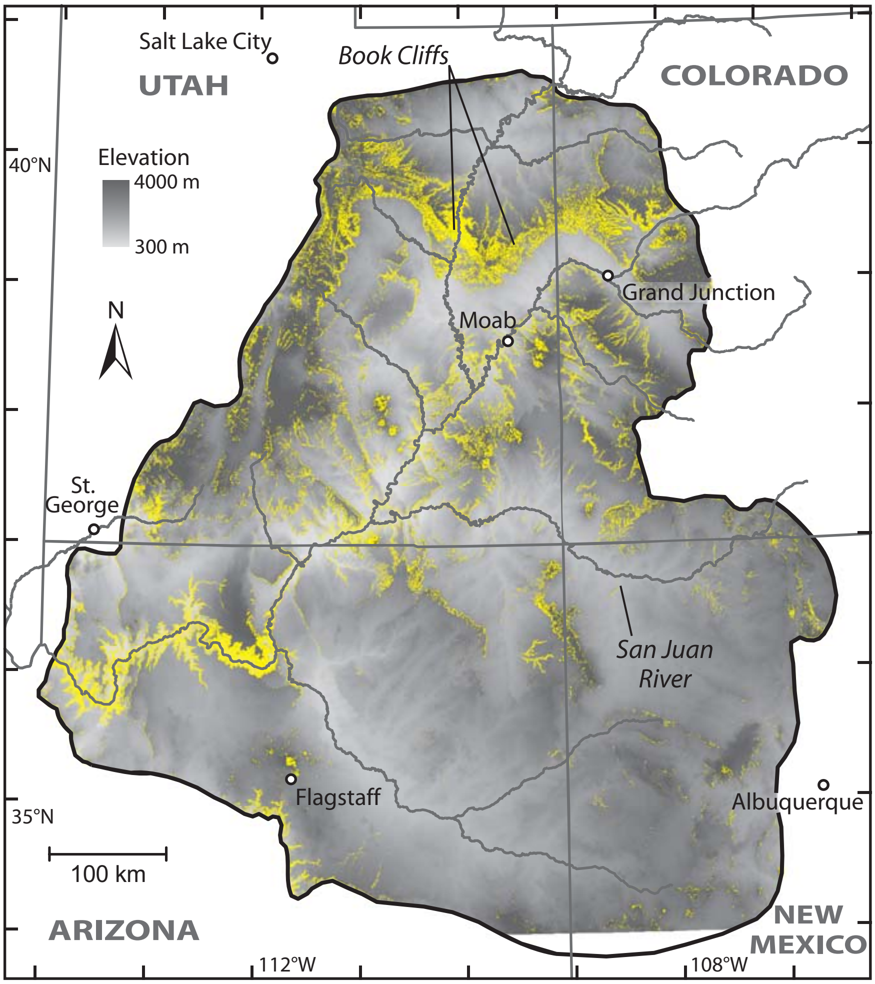


Figure 3. Map of slopes greater than 20° (in yellow) on the Colorado Plateau as determined from 30-m digital-elevation models.

Influence of Rainfall Distribution and Intensity

The Colorado Plateau has an arid to semi-arid climate characterized by summer convective thunderstorms and occasional warm winter storms. Most debris flows occur in summer (Webb et al., 1989, 1999, 2000, 2004), when convective thunderstorms yield intense rainfall (Hereford and Webb, 1992; Hereford et al., 2002). Webb et al. (2000) report no relation between debris-flow occurrence in Grand Canyon and total seasonal precipitation; instead, they hypothesize that debris-flow occurrence is better related to wet periods where antecedent soil moisture can accumulate over short (~1-week) periods.

Long-term climate stations, particularly ones that report instantaneous or even hourly rainfall, are few on the Colorado Plateau (Hereford et al., 2002) and typically are not present in the source areas of most debris flows (Webb et al., 2000). The low density of rainfall stations, and particularly ones that record instantaneous or hourly precipitation, precludes geospatial analysis of potential rainfall patterns that might affect debris-flow occurrence. Maps depicting precipitation at 10- to 100-yr recurrence intervals, which are the only regional data on rainfall intensity, have little spatial resolution in this region; instead, they mirror the topography (http://hdsc.nws.noaa.gov/hdsc/pfds/sa/ut_pfds.html, accessed 5 December 2006). Given the highly localized nature of summer thunderstorms on the Colorado Plateau and its close relation to topography, digital-elevation models probably are the best way to incorporate the rainfall factor into an analysis of regional debris-flow occurrence.

Influence of Sediment Sources

Sedimentary bedrock on steep slopes or in cliffs, combined with weathering processes, provides an abundance of source material having a wide range of particle sizes (Fig. 2). This bedrock has been heavily dissected into a plateau and canyon landscape, resulting in numerous steep cliffs, along which colluvium is stored with high potential energy. Given that Colorado Plateau river canyons are active erosional features cut through a landscape consisting mostly of sedimentary bedrock, the supply of poorly sorted sediment for debris flows is essentially unlimited. The abundant sedimentary bedrock, and particularly alternating resistant and easily weathered strata (Fig. 2A), create an ideal source of sediment for debris flows. Rockfall in these cliffs (Hereford and Huntoon, 1990) accumulates in colluvial aprons (Fig. 2B), some of which form extensive mantles over bedrock slopes (Fig. 2C).

The bedrock of the Colorado Plateau is dominated by Upper Paleozoic, Mesozoic, and Cenozoic sedimentary strata (Baars, 2000). Exceptions are in Grand Canyon, where Middle and Lower Paleozoic sedimentary strata and Proterozoic igneous and metamorphic rocks are exposed (Fig. 2C), and Westwater Canyon (Fig. 1), where Proterozoic igneous and metamorphic rocks again are exposed (Stokes, 1988). Upper Paleozoic rocks in the Colorado Plateau are mostly of marine origin. In the Mesozoic, deposition was dominated by coastal and continental processes, a trend that continued into the Cenozoic (Hintze, 1988; Stokes, 1988). During the Tertiary, an abundance of lacustrine deposits accumulated in large closed basins in northern Arizona and central Utah. Transitions between different depositional environments and source materials have resulted in interbedded sandstones, mudstones, and shales that weather into the characteristic slopes and cliffs of the Colorado Plateau (GSA Data Repository Table DR1)[1].

Fine-grained bedrock contributes to debris-flow occurrence in several ways. It is the primary source of clay; debris flows on the Colorado Plateau typically contain ~4% silt plus clay (Webb et al., 2000), and the small amounts of clay contribute to the cohesive slurry required for long-distance transport (Fig. 2D). Debris flows with lower clay contents (~1% or less), such as those that occur at Prospect Canyon in Grand Canyon (Webb et al., 1999), flow short distances before losing too much mass to sustain boulder transport. Certain units of fine-grained bedrock fail readily, either producing debris flows directly

[1]GSA Data Repository Item 2008024, bedrock units on the Colorado Plateau bearing significant fine-grained layers as well as all clay mineralogy and major-cation concentrations (the list of units is given in Table DR1, and a list of the units that we sampled is given in Table DR2), is available at www.geosociety.org/pubs/ft2008.htm. Requests may also be sent to editing@geosociety.org.

or storing sediment to colluvial deposits, which can fail later. Strata of fine-grained bedrock in cliff faces, whether shales or thinly layered limestones, form gentler slopes that are colluvium storage sites in an otherwise high-relief setting. Erosion of fine-grained bedrock destabilizes the overlying cliff-forming lithologies, particularly limestones, which eventually contribute rockfalls or avalanches that deliver larger particles into colluvial storage.

In Grand and Cataract Canyons, previous studies suggest that clay mineralogy and major-cation composition of bedrock units is strongly related to the spatial distribution of debris flows. Griffiths et al. (2004) identified eight fine-grained bedrock units in Marble and Grand Canyons that are associated with historical debris flows. Using data obtained from repeat photography of historical debris flows, they developed a debris-flow probability map for Grand and Marble Canyons based on drainage-basin area, aspect of the Colorado River, and geological variables of the distance, height, and gradient from the Paleozoic Hermit Formation and/or Supai or Tonto Groups to the river. In Cataract Canyon, Webb et al. (2004) reported that the Paleozoic Halgaito Formation is associated with debris flows in that reach.

Previous research indicates that, at least locally, fine-grained bedrock units with high contents of single-layer clays, such as the Hermit and Halgaito Formations, contribute to debris flows, whereas units with abundant multilayer smectites, such as the Mancos and Tropic Shales, do not. Larsen (2003) suggested the same association between single-layer clays and debris-flow occurrence along the Green River in Canyon of Lodore, north of the Colorado Plateau. Larsen's (2003) observations add to the hypotheses of Griffiths (1995) and Rudd (2005) that debris-flow occurrence on the Colorado Plateau is related to the distribution on single-layer clays in fine-grained bedrock.

METHODS

Identification of Relevant Fine-Grained Bedrock

We identified 85 mapped bedrock units on the Colorado Plateau that contain distinct strata of fine-grained sediment, at least 1-m thick and consisting primarily of silt and clay, as potential sources of debris-flow sediment. These layers generally are argillaceous and classified as shales, mudstones, siltstones, or claystones. Units containing thinner layers or discontinuous lenses of fine-grained sediment were not included. We consulted United States Geological Survey (USGS) 1:250,000 scale geologic maps—the only map data with a consistent scale on the Colorado Plateau—to determine the location and extent of these units (Table DR1; see footnote 1). We did not consider topographic position or slope in our selection process.

We conducted extensive field work to classify the selected geologic units as debris-flow producers, nonproducers, or indeterminate effect on debris-flow occurrence (Table DR2). We only consider debris flows that flowed long distances (>1 km) from the source outcrop or colluvium. Debris-flow producers were determined based on other evidence, either from our observations or from the literature (e.g., Brabb et al., 1989; see Table DR2), that Holocene debris flows either originated in the unit or from colluvium generated from that unit. As the name implies, nonproducers have no evidence of Holocene debris-flow occurrence; units producing small debris flows that did not travel beyond high-angle slopes (e.g., the Honaker Trail Formation in Cataract Canyon) are classified as nonproducers. We recognize that basing the nonproducer category on absence of evidence makes this category less robust than the producer category. There was insufficient observational evidence for a few units to classify them as either producer or nonproducer of debris flows, and these are classified as indeterminate units.

Sample Collection

In Grand and Cataract Canyons, we collected samples from fine-grained rock units known to produce Holocene debris flows (Griffiths et al., 2004; Webb et al., 2004), from topographically lower colluvial deposits that produced debris flows, and from historical debris-flow deposits. A total of eight fine-grained bedrock units produce debris flows in Grand Canyon; similarly, five units produce debris flows in Cataract Canyon and vicinity (Table 1). We collected 17 and 16 samples of colluvium and 14 and 12 samples of debris-flow deposits from Grand and Cataract Canyons, respectively (Table 1). We sampled <32-mm diameter (B-axis) fractions of colluvium and debris-flow deposits; we then extracted <2-mm samples for major-cation analysis and <4- m samples for clay-mineralogy analysis.

Of the 85 fine-grained bedrock units identified from geologic maps, we determined that 52 units were of significant spatial extent or in steep topographic positions to warrant sampling to evaluate the influence of clay mineralogy and major-cation concentration. We collected 60 samples from these 52 fine-grained bedrock units (Fig. 1). Where a single formation has several members containing fine-grained beds more than 1-m thick, samples were taken only from members that were judged to differ significantly from each other in terms of environment of deposition or clay content. We eliminated one of these samples owing to insufficient clay content for analysis, resulting in a total of 59 samples from 52 units (Table DR3). For the purposes of sample independence, we averaged the results from multiple samples from the same unit. From

TABLE 1. CLAY MINERALOGY OF FINE-GRAINED UNITS, COLLUVIUM, AND DEBRIS-FLOW DEPOSITS IN GRAND AND CATARACT CANYONS

Sample type	Illite (weight %)	Kaolinite (weight %)	Montmorillonite (weight %)	Other[†] minerals (weight %)
Grand Canyon				
Debris-flow producing bedrock (n = 8)[‡]				
Mean	53	27	2	18
Standard deviation	11	14	2	11
Debris-flow producing colluvium (n = 17)[§]				
Mean	33[#]	41	10	17
Standard deviation	13	19	16	8
Debris-flow deposits (n = 14)[§]				
Mean	40[#]	28	9	24
Standard deviation	16	9	16	11
Cataract Canyon				
Debris-flow producing bedrock (n = 5)[‡]				
Mean	46	33	1	20
Standard deviation	15	14	1	17
Debris-flow producing colluvium (n = 16)[§]				
Mean	23[#]	40	8	29[#]
Standard Deviation	8	13	12	9
Debris-flow deposits (n = 12)[§]				
Mean	26	37	6	31
Standard deviation	15	18	7	17

Note: Minerals were identified by X-ray diffraction analysis (Starkey et al., 1984).
[†] Other clay minerals include quartz, carbonate, and a variety of trace minerals.
[‡] From Table DR3.
[§] From Table DR4.
[#] The distribution of concentrations of this mineral are significantly different (p >0.95) between bedrock and colluvium or debris-flow deposits based on the Kolmogorov-Smirnov two-sample nonparametric test. The concentrations of clay minerals were not significantly different between colluvium and debris-flow deposits.

TABLE 2. CLAY MINERALOGY AND MAJOR-CATION CHEMISTRY OF FINE-GRAINED BEDROCK ON THE COLORADO PLATEAU

	Illite[†] (weight %)	Kaolinite[†] (weight %)	Montmorillonite[†] (weight %)	Other minerals[‡] (weight %)	Calcium (Ca^{++}) (μg/g)	Sodium[†] (Na^{+}) (μg/g)	Magnesium[†] (Mg^{++}) (μg/g)	Potassium[†] (K^{+}) (μg/g)
HOLOCENE DEBRIS-FLOW PRODUCERS (n = 21)[§]								
	Clay minerals				Major cations			
Mean	44	27	5	24	30	32	25	10
Standard deviation	17	14	13	15	18	21	13	9
NO HOLOCENE DEBRIS FLOWS (n = 17)[§]								
	Clay minerals				Major cations			
Mean	16	9	51	25	28	56	13	2
Standard deviation	19	8	30	22	26	32	15	3

[†] The distribution of concentrations of this mineral are significantly different (p >0.95) between bedrock units producing Holocene debris flows or not based on the Kolmogorov-Smirnov two-sample nonparametric test.

[‡] Other clay minerals include quartz, carbonate, and a variety of trace minerals.

[§] From Table DR3.

our field observations of the 52 units sampled, we determined that 21 units or subunits produced Holocene debris flows, 17 units did not produce Holocene debris flows (Table 2), and 14 were classified as indeterminate (Table DR2).

Laboratory Analysis

Mineralogy of the debris-flow deposits, colluvium, and bedrock was determined through X-ray diffraction analyses of clay-size fractions (Starkey et al., 1984). Minerals identified include kaolinite, illite, and smectite, as well as clay-size particles of quartz, carbonate, and other trace minerals. Results are given in weight percent with an overall error range of ±20%; this error is less for more abundant clay minerals and likely is higher for those at low abundance (S.J. Sutley, USGS, 2006, written commun.). Because this uncertainty varies in a nonuniform way, it cannot be meaningfully included in our statistical analyses.

The concentrations of soluble cations (Na^+, K^+, Mg^{2+}, and Ca^{2+}) of the clay-size fraction were determined using an ammonium acetate extract and analysis using an inductively coupled plasma mass spectrometer (ICP-MS). Results are in micrograms per gram of rock (g/g) and milliequivalents per hundred grams (meq/100 g); all concentrations are converted to units of g/g. The uncertainty of these analyses is ±10% of the mean (A. Ray-Maitra, University of Arizona, 2006, written commun.).

Statistical Analysis

Several statistical analyses were used to evaluate whether fine-grained bedrock units that produce Holocene debris flows (n = 21) could be differentiated from those that do not produce debris flows (n = 17) on the basis of clay mineralogy and major-cation concentration. Debris-flow producing bedrock units (n = 13), colluvium (n = 33), and debris-flow deposits (n = 26) in Grand and Cataract Canyons were evaluated in the same manner. To avoid parametric assumptions, such as whether or not data are from a Gaussian distribution, we used the nonparametric, two-sample Kolmogorov-Smirnov (KS) test to compare producing and nonproducing bedrock, colluvium, and debris-flow deposits. The KS test compares empirical distributions based on sample statistics to determine whether populations are identical or not (Conover, 1980, p. 368). Likewise, the nonparametric Kruskal-Wallis (KW) test, which essentially tests whether the medians of two populations are similar (Conover, 1980, p. 229), was used to discriminate between producing and nonproducing bedrock units. A standard of 95% probability ($p < 0.05$) for acceptance of the differences between or among means or variances was used for all analyses.

Indicator-species analysis (ISA) (Dufrêne and Legendre, 1997; McCune and Grace, 2002) is a multivariate technique used to identify statistically significant characteristics of groups of variables. It was developed to segregate species of plants and animals that characterize biological assemblages (McCune and Grace, 2002). We applied it to our data to determine what clay minerals and major cations characterize debris-flow producing fine-grained bedrock. The implementation of ISA that we used evaluates statistical significance on the basis of a Monte Carlo analysis of 10,000 replications. This significance was combined with the KW test to statistically distinguish debris-flow producers from nonproducers.

Principal-components analysis (PCA), a multivariate-statistical tool (Haan, 1977), was used to evaluate whether fine-grained bedrock units that produce debris flows could be differentiated from those that do not produce debris flows (Tables DR2 and DR3). The debris-flow potential of a bedrock unit is independent from the analysis and is used to evaluate the statistical results. PCA is an ordination technique that extracts eigenvectors from a self-similar table of correlation coefficients—in our case, correlations among rock units on the basis of clay mineral percentages and major-cation concentrations—to separate variables (fine-grained bedrock units) into groups along nonrotated PCA axes, the number of which equals the number of variables. The PCA axes have no physical meaning but instead represent the amount of variance explained by the first eigenvector.

Because the first two PCA axes accounted for most of the sample variance, we chose to use only the first two axes for our graphical interpretation of the influence of fine-grained bedrock units on debris-flow potential. After plotting PCA-axis 1 and PCA-axis 2, we interpreted the clustering of fine-grained bedrock units according to our initial categorizations of units as Holocene debris-flow producers, nonproducers, and indeterminate units. A second PCA was performed using only the independent variables (clay minerals and major cations) listed as statistically significant in both the KW and the ISA. The results of this second PCA showed that our initial classification of debris-flow producing units could be modified for further geographic analyses.

Maps of Debris-Flow Potential

We superimposed regional maps of slope and geology to determine the intersection between slopes >20° and fine-grained bedrock units identified as debris-flow producers using PCA. This intersection is a map of debris-flow potential for the entire Colorado Plateau. Slope was calculated from a 30-m digital-elevation model, which represents the highest resolution topography available for the entire Plateau. Because digital geologic maps are not available for the entire Plateau, exposures of fine-grained bedrock were digitized from USGS 1° × 2° geologic maps at scales of 1:62,500 and 1:100,000 (GSA Data Repository Fig. DR1). Exposures in the Grand Canyon area were imported directly from digital versions of 30° × 60° geologic maps at 1:100,000 scale. Geologic data at these scales were not available for ~25% of the southern and western parts of the Colorado Plateau (see Fig. DR1). Hand-digitizing large paper maps at these small scales necessarily introduced a certain degree of error—as much as 500 m at some locations—which becomes particularly significant when trying to correlate narrow regions of interest, such as the steep slope and exposed lithologies along cliff faces.

TABLE 3. RESULTS OF KRUSKAL-WALLIS AND INDICATOR-SPECIES ANALYSES

Mineral/cation	Indicator value (IV)[‡]	p[§]	Kruskal-Wallis probability (ρ)[#]
Holocene debris-flow producers (n = 21)[†]			
K^+	82	0.000[††]	0.000[††]
Kaolinite	74	0.000[††]	0.000[††]
Illite	72	0.000[††]	0.000[††]
Mg^{++}	66	0.000[††]	0.006[††]
Quartz	51	0.56	0.060
Ca^{++}	52	0.66	0.46
Other minerals	46	0.99	0.67
No Holocene debris flows (n = 17)[†]			
Montmorillonite	86	0.000[††]	0.000[††]
Na^+	64	0.01[††]	0.017[††]
Carbonate	42	0.16	0.16

[‡] IV is the observed indicator value calculated by indicator-species analysis (McCune and Grace, 2002).
[§] p—proportion of 10,000 Monte Carlo randomized trials that replicate or exceed observed IV.
[#] ρ—Kruskal-Wallis probability that difference in the mineral/cation distribution between shale classes is random.
[††] indicates the variable is significant to the group in indicator species analysis ($p < 0.05$) or indicates a difference in variable between the groups for Kruskal-Wallis tests ($\rho < 0.05$).

RESULTS

Comparison of Bedrock, Colluvium, and Debris-Flow Deposits in Grand and Cataract Canyons

With the exception of illite content, debris-flow producing bedrock on the Colorado Plateau has a similar clay mineralogy and major-cation concentration to associated colluvium and debris-flow deposits in Grand and Cataract Canyons (Table 1). The clay mineralogy is not different between colluvium and debris-flow deposits, either in Grand or Cataract Canyons or between the two canyons. Despite the decrease in illite content between bedrock (~50%) and unconsolidated deposits (23%–33%), the fraction of illite and kaolinite, which represents most of the single-layer clays, is not significantly different among the three sample groups (~60%–80%). These results show that clay-mineral content is consistent from bedrock source to talus accumulations in colluvium to debris-flow deposits, confirming that clay mineralogy and major-cation chemistry is associated with debris-flow occurrence.

Fine-Grained Bedrock on the Colorado Plateau

On average, fine-grained bedrock that produces debris flows can be distinguished from nonproducing bedrock on the basis of distinctive clay mineralogy and differences in major-cation concentrations (Table 2). With a few exceptions, debris-flow producers are uniformly low in montmorillonite (5%) and high in illite and kaolinite (71%); conversely, fine-grained bedrock that does not produce debris flows has lower illite and kaolinite (25%) and higher montmorillonite (51%) content. Other minerals, including clay-sized carbonate, quartz, and trace minerals, are not different among producers and nonproducers. Of the four major cations analyzed, K^+ and Mg^{2+} concentrations are higher in debris-flow producers and Na^+ is higher in nonproducers (Table 2).

Indicator-species analysis (ISA) shows that fine-grained bedrock can be discriminated on the basis of clay mineralogy and major-cation concentrations (Table 3). Fine-grained bedrock that produces Holocene debris flows has high concentrations of kaolinite, illite, K^+, and Mg^{2+}. In contrast, fine-grained bedrock that does not produce debris flows has high concentrations of montmorillonite and Na^+ (Table 3). These results indicate a strong mineralogical difference between debris-flow producing and nonproducing units.

Principal-components analysis (PCA) was used to further examine our results for consistencies between the two groups of bedrock units. An initial PCA (64.8% of variance explained) using all data yielded a distinctive clustering of producers and nonproducers with some notable exceptions (Fig. 4A). These include the clustering of the nonproducing Arapien and Kayenta Formations and the indeterminate undifferentiated Cutler and Moenave among the debris-flow producers. Also, debris-flow producing Monitor Butte Member of the Chinle Formation, the North Horn Formation, and the Straight Cliffs Formations were clustered among the nonproducers, along with nine indeterminate units (Fig. 4A). Three units are attributable to neither of the two main groups: one nonproducer (the Fruitland Formation) and two indeterminate units. These results suggest a classification accuracy of >85% within the main groups and some ambiguity between the two.

Using just the variables in Table 3 that are statistically significant using KW and ISA (kaolinite, illite, montmorillonite, K^+, Mg^{2+}, and Na^+), a second PCA (74.7% of the variance explained) resulted in a tighter clustering of debris-flow producers and nonproducers (Fig. 4B), but some ambiguity and exceptions remain. The nonproducing Arapien and the indeterminate Cutler and Moenave Formations remain clustered with the debris-flow producers, and the North Horn and Straight Cliffs Formations are clustered among nonproducers (Fig. 4B). Of the 14 undetermined units, ten cluster as nonproducers, and two, the Moenave and Cutler Formations, cluster as a debris-flow producers. One nonproducer (the Kayenta Formation) and two indeterminate units are in neither of the two main groupings.

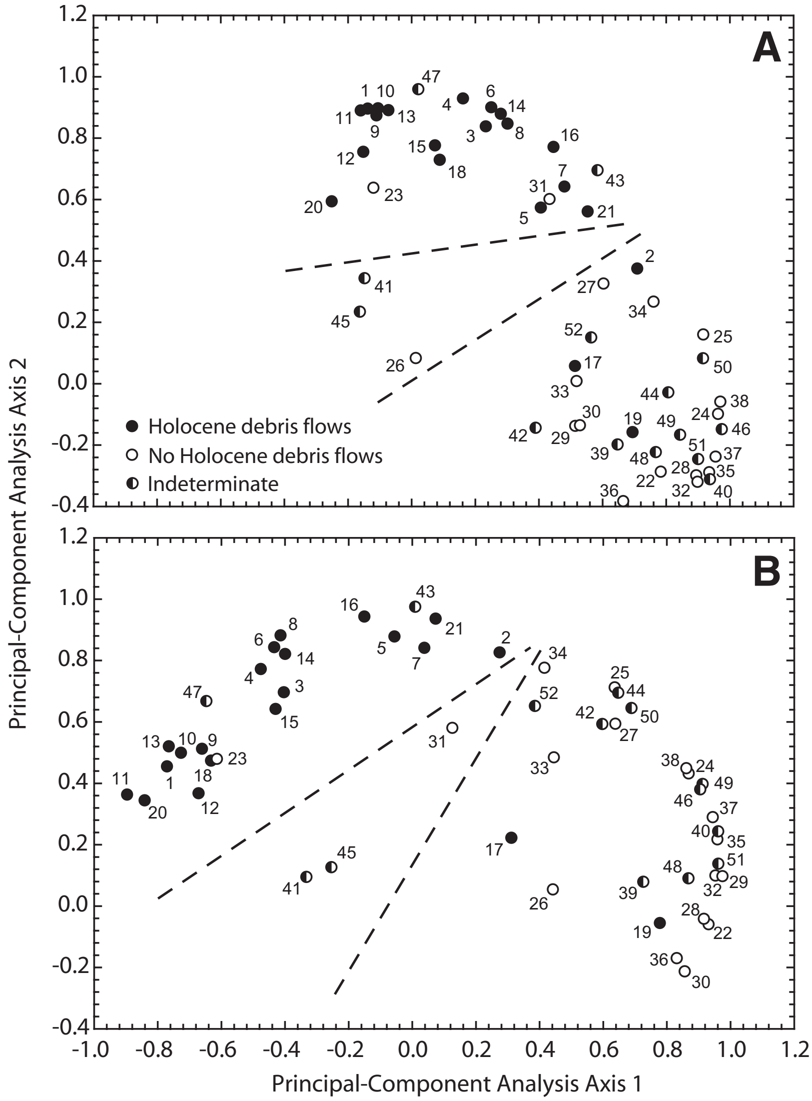
The units that do not cluster with similar units in terms of debris-flow properties are exceptions that may be related to the initiation mechanism for debris flows. For example, the Straight Cliffs Formation is high in montmorillonite (>60%; Table DR3), yet it is known to produce Holocene debris flows that run out from deep-seated landslide failures (Williams, 1984) instead of the more typical shallow-failure mechanism. Because the undifferentiated Cutler Formation has lateral facies changes that result in differentiation into several debris-flow producing units, such as the Elephant Canyon, Organ Rock, and Halgaito Formations, its grouping with debris-flow producers is reasonable. As previously discussed, we limit our considerations to debris flows initiated during failures of steep slopes during intense rainfall and do not consider the other failure mechanisms of saturation of colluvial slopes or mobilization of debris flows from landslides, which are less common in Holocene climate on the Colorado Plateau. In contrast, the Arapien Formation, which is not known to produce debris flows, is high in illite and kaolinite and low in montmorillonite. The lack of debris flows from this formation may stem from its occurrence on slopes generally <20°.

Map of Regional Debris-Flow Potential

We identified locations with a potential for Holocene debris flows by mapping the intersection of slopes greater than 20° (Fig. 3) and extent of fine-grained bedrock identified as debris-flow producing units (Fig. 4). The resulting map (Fig. 5) agrees closely with the observational evidence of where Holocene debris flows have occurred on the Colorado Plateau (Table DR2). Regionally, debris-flow potential is highest on the Colorado Plateau across Utah, Colorado, and the Grand Canyon area of Arizona, and is low across the remainder of the Arizona and New Mexico parts of the plateau, owing to a predominantly low-relief landscape (Figs. 3 and 5). This low-relief landscape continues into most of the unmapped zones along the southern edge of the plateau, suggesting that debris-flow potential is likely low in those areas as well.

Debris flows are expected to occur where widespread exposures of debris-flow producing bedrock are coincident with broad areas of high-relief landscape. These conditions most commonly occur above the Roan Cliffs and along the Desolation and Gray Canyons of the Green River in northern Utah (Fig. 5). In this location, broad expanses of Colton and Wasatch Formations are heavily dissected by numerous steep drainages and canyons. The high spatial potential for debris flows along Gray and Desolation Canyons of the Green River corresponds with our observations that most tributaries in these canyons have had at least one historical debris flow. Similar conditions for widespread debris-flow potential occur on the Wasatch Plateau to the west, where frequent ridgelines and cliffs cut across broad exposures of the Flagstaff Formation and other debris-flow producing units (Fig. 5).

In other parts of the Colorado Plateau, debris flows are expected where debris-flow producing units occur along the edges of plateaus or are exposed in the walls of river canyons. The plateau effect is clearly evident in exposures of the Hermit Formation along the edges of Grand Canyon, the Wasatch Formation along the edge of Grand Mesa, the Morrison Formation along the eastern side of Black Mesa, and the Colton Formation along the uppermost edge of the western end of the Book Cliffs (Fig. 5). The canyon effect is well illustrated in Grand Canyon, where bands of debris-flow potential on the map highlight debris-flow producing strata exposed as the canyon cuts to the south and east (Fig. 5).



Holocene debris flows
1 Bright Angel
2 Chinle - Mon. Butte
3 Colton
4 Dox
5 Elephant Canyon
6 Esplanade
7 Flagstaff
8 Galeros
9 Hakatai
10 Halgaito
11 Hermit
12 Kwagunt
13 Moenkopi - Lower
14 Moenkopi - Upper
15 Morrison - Br. Basin
16 Morrison - Salt Wash
17 North Horn
18 Organ Rock
19 Straight Cliffs
20 Wanakah
21 Wasatch

No Holocene debris flows
22 Animas
23 Arapien
24 Bidahochi
25 Chinle - Petr. Forest
26 Fruitland
27 Green River - Middle
28 Green River - Upper
29 Green River - SS/LS
30 Honaker Trail
31 Kayenta
32 Kirtland
33 Lewis
34 Mancos
35 Nacimiento
36 Park City
37 San Jose
38 Tropic

Indeterminate
39 Carmel
40 Cedar Mountain
41 Claron
42 Curtis
43 Cutler
44 Duschene River
45 Farrer
46 Kaiparowits
47 Moenave
48 Stump
49 Summerville
50 Tuscher
51 Uinta
52 Wahweap

Figure 4. Principal-component analysis (PCA) of clay-mineral content and major-cation concentration of fine-grained bedrock on the Colorado Plateau. The axes do not have direct chemical or mineralogical interpretation; please see the text for an explanation of PCA axes. (A) First two axes of a PCA of Holocene debris-flow producers versus nonproducers using all data (from Table DR3). The dashed lines indicate our interpretation of the separation in the variables. (B) Reanalysis PCA using only the variables in Table 3 that are significant in both the indicator-species analysis (ISA) and Kruskal-Wallis nonparametric analysis (KW).

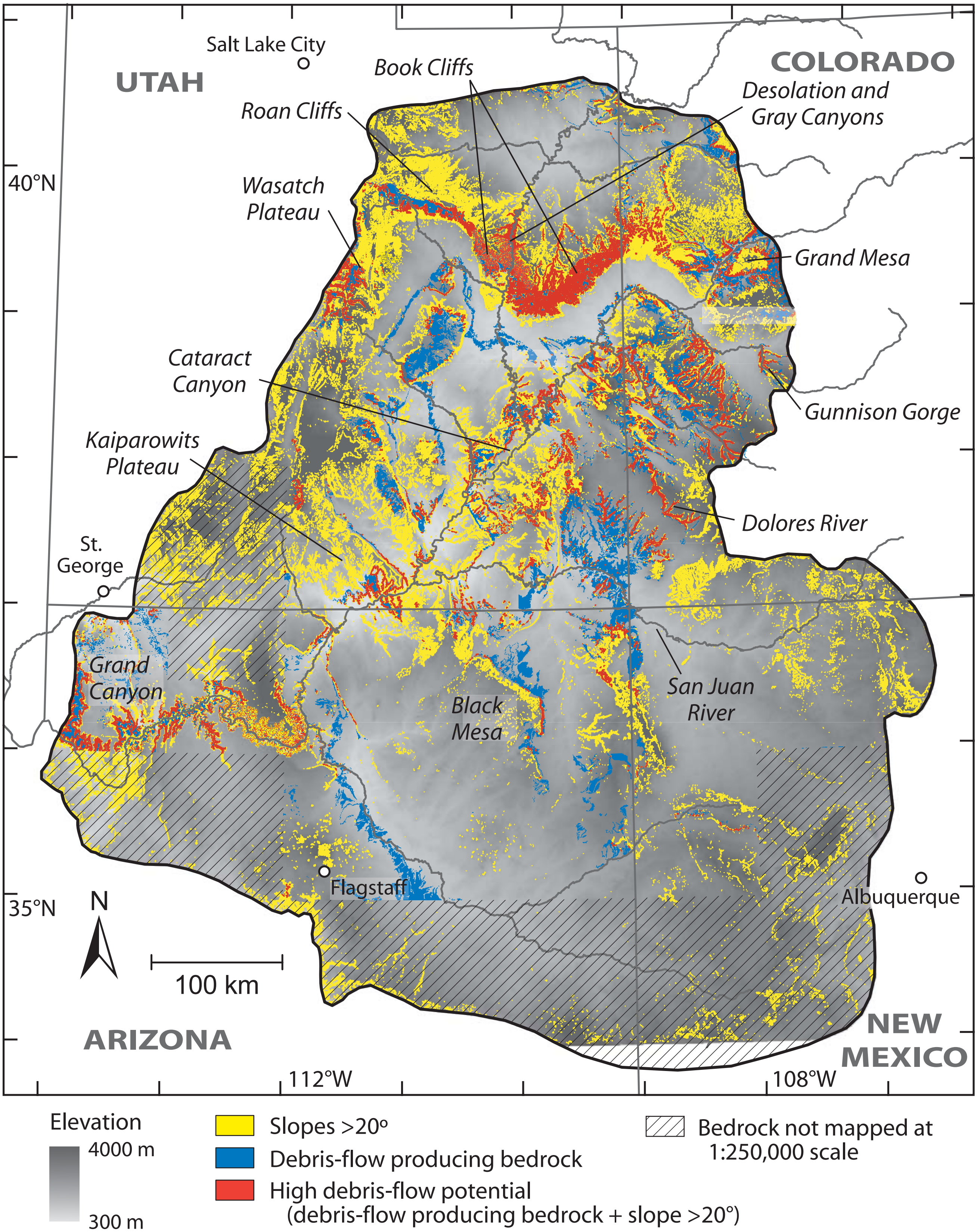


Figure 5. Map of the Colorado Plateau (scale 1: 1,000,000) showing the intersection of areas where slope >20° (Fig. 3) and the location of fine-grained bedrock units identified as debris-flow producers (Fig. 4B). Areas on the south and southeast parts of the Colorado Plateau have no data because of insufficient geologic maps at 1:250,000 scale (Fig. DR1).

High debris-flow potential is also notable on a smaller scale in southwestern Colorado where numerous river canyons cut through the Morrison Formation, such as along the upper Dolores River, the upper San Miguel River, and the Gunnison River in the Gunnison Gorge (Fig. 5).

The limitations of evaluating debris-flow potential at this small scale (1:1,000,000) are evident in Cataract Canyon, where debris-flow activity is common, but debris-flow potential is not apparent in Figure 5. This results from the thin Halgaito Shale, which is exposed in near vertical cliffs, making it difficult to portray at 1:250,000 scale. Similarly, the Utah canyons of the San Juan River are not expected to have widespread debris flows because of the scattered exposures of debris-flow producing bedrock, again Halgaito Shale. Overall, the mapped debris-flow potential follows our understanding of debris-flow occurrence in river canyons.

DISCUSSION AND CONCLUSIONS

Holocene debris-flow occurrence on the Colorado Plateau is related to steep topography, intense or prolonged precipitation, and the presence of fine-grained bedrock exposed high on cliffs and bearing single-layer clays such as illite and kaolinite and relatively high concentrations of potassium and magnesium. We found that fine-grained bedrock and colluvium associated with debris-flow initiation in Grand and Cataract Canyons had similar clay mineral and major-cation concentrations to debris-flow deposits, although illite content was higher in bedrock than in either colluvium or the debris-flow deposits. Multivariate-statistical analyses differentiate fine-grained bedrock units that produce Holocene debris flows from those that do not. Fine-grained bedrock containing abundant montmorillonite, clay-sized carbonates, and sodium generally have not produced Holocene debris flows. We underscore that the mechanism of debris-flow mobilization from landslides or saturated failure of bedrock or colluvium, which are uncommon in Holocene climates on the Colorado Plateau, were not considered and that some of the ambiguity in our classification can be attributed to that infrequent occurrence.

Although other work has suggested that aspect also influences debris-flow frequency (Griffiths et al., 2004), we did not evaluate that effect in this study. Our simple spatial analysis indicates that debris-flow occurrence on the Colorado Plateau is associated with the co-location of steep slopes and fine-grained bedrock units containing mostly single-layer clays. Aspect, which may locally influence rainfall intensity, appears to be a secondary effect that requires further study.

The type of clay minerals—whether single layer or multilayer—could influence debris-flow occurrence in several ways. Outcrops of fine-grained bedrock containing single-layer clays tend to have joints that allow deep percolation of rainfall, which would facilitate bedrock failures. Multilayer clays commonly swell after the first rains, sealing the surface and minimizing deep percolation of rainfall, which suggests that mass failures would be unusual unless saturation during prolonged rainfall occurs, a rare occurrence on the Colorado Plateau. While outcrops of bedrock containing multilayer clays typically produce prodigious amounts of sediment, leading to extremely high concentrations in rivers (Beverage and Culbertson, 1964), they generally do not have mass failures under Holocene climates with some notable exceptions (Williams, 1984; Boison and Patton, 1985; Jibson and Harp, 1996).

Our results on the influence of clay mineralogy and major-cation concentrations contrast with results from other regions and may represent differences between shallow- and deep-seated mass failures in debris-flow initiation. In the Coast Range of California, deep-seated landslides occur on slopes having clay contents high in multilayer smectites and low in single-layer kaolinite (Borchardt, 1977); it is likely that at least some of these landslides mobilized into debris flows. A complex suite of landslides in Zion Canyon, Utah, which last moved in 1992, had 70% montmorillonite and 30% illite (Jibson and Harp, 1996). Shallow-seated failures on the Colorado Plateau appear to be related to single-layer clays. This suggests that surface sealing may be one reason why multilayer clays generally do not produce Holocene debris flows on the Colorado Plateau with the exceptions as previously discussed.

Colluvial deposits containing abundant multilayer clays, which are commonly found beneath near-vertical exposures of Mancos Shale in the Book Cliffs, also undergo surface sealing when first wetted, limiting deep infiltration. Nevertheless, these colluvial deposits, where they line channels, could be undercut, creating failures that potentially could mobilize into debris flows. Finally, prolonged precipitation could eventually saturate these deposits and cause deep-seated landslide failures of the type known to have occurred in limited areas, such as the east side of the Kaiparowits Plateau (Williams, 1984; Boison and Patton, 1985).

Clay chemistry and mineralogy could be important to sustained debris flow, because electrochemical attraction among clay particles may help increase debris-flow matrix viscosity, one condition deemed necessary to support large clasts (Hampton, 1975; Pierson and Costa, 1987; Iverson, 1997). The difference in molecular structure between the kaolinite group of minerals (e.g., illite and kaolinite) and the smectite clays (e.g., montmorillonite and bentonite) provides one possible explanation for the association between single-layer clays and debris-flow occurrence. The kaolinite group is composed of alternating tetrahedral and octahedral layers, while smectite clays are composed of groups of three layers, one octahedral layer held between two tetrahedral layers (Blatt et al., 1972). It is possible that this structural difference on the molecular level influences debris-flow rheology, because smectite has a greater yield strength at lower sediment concentrations than does kaolinite, and smectite clays swell when wetted. However, we cannot rule out the possibility that debris flows with high matrix content of multilayer clays could flow long distances; indeed, one debris-flow deposit in Grand Canyon had a high content of montmorillonite (Melis et al., 1994). Again, this suggests that the role of clay mineralogy may be related to surface sealing and failure mechanism, not flow mechanics.

The association of single-layer clays with debris-flow occurrence in arid and semiarid climates suggests application to hazard analysis in other geological settings. Debris flows commonly occur in certain types of granitic terrane (Wells et al., 1987; Whipple and Dunne, 1992), and many types of acidic intrusive rocks weather to clay-mineral suites dominated by single-layer clays. Feldspars, in particular, weather to kaolinite, particularly in an arid climate (Birkeland, 1984); in contrast, alkaline rocks, notably basalt, tend to weather to smectites. This suggests a possible means of discriminating potential debris-flow occurrence in arid and semiarid environments among the various types of igneous terranes.

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REFERENCES CITED

Baars, D.L., 2000, The Colorado Plateau: Albuquerque, University of New Mexico Press, 254 p.

Beverage, J.P., and Culbertson, J.K., 1964, Hyperconcentrations of suspended sediment: American Society of Civil

Engineers: Journal of the Hydraulics Division, v. 90, p. 117–126.
Birkeland, P.W., 1984, Soils and geomorphology: New York, Oxford University Press, 372 p.
Blackwelder, E., 1928, Mudflow as a geologic agent in semiarid mountains: Geological Society of America Bulletin, v. 39, p. 465–494.
Blatt, H., Middleton, G., and Murray, R., 1972, Origin of sedimentary rocks: Englewood Cliffs, New Jersey, Prentice-Hall, 634 p.
Boison, P.J., and Patton, P., 1985, Sediment storage and terrace formation in Coyote Gulch basin, south-central Utah: Geology, v. 13, p. 31–34, doi: 10.1130/0091-7613(1985)13<31:SSATFI>2.0.CO;2.
Borchardt, G.A., 1977, Clay mineralogy and slope stability: California Division of Mines and Geology Special Report 133, 15 p.
Brabb, E.E., Wieczorek, G.F., and Harp, E.L., 1989, Map showing 1983 landslides in Utah: U.S. Geological Survey Miscellaneous Field Studies Map MF-2085, 1 sheet, scale 1:500,000.
Brabb, E.E., Colgan, J.P., and Best, T.C., 1999, Map showing inventory and regional susceptibility for Holocene debris flows and related fast-moving landslides in the conterminous United States: U.S. Geological Survey Miscellaneous Field Studies Map MF-2329, 1 sheet, scale 1:2,500,000.
Conover, W.J., 1980, Practical nonparametric statistics: New York, John Wiley and Sons, 493 p.
Cooley, M.E., Aldridge, B.N., and Euler, R.C., 1977, Effects of the catastrophic flood of December, 1966, North Rim area, eastern Grand Canyon, Arizona: U.S. Geological Survey Professional Paper 980, 43 p.
Dufrêne, M., and Legendre, P., 1997, Species assemblages and indicator species: The need for a flexible asymmetrical approach: Ecological Monographs, v. 67, p. 345–366.
Elliott, J.G., and Hammack, L.A., 1999, Geomorphic and sedimentologic characteristics of alluvial reaches in the Black Canyon of the Gunnison National Monument, Colorado: U.S. Geological Survey Water-Resources Investigations Report 99-4082, 67 p.
Garvin, C.D., Hanks, T.C., Finkel, R.C., and Heimsath, A.M., 2005, Episodic incision of the Colorado River in Glen Canyon, Utah: Earth Surface Processes and Landforms, v. 30, p. 973–984, doi: 10.1002/esp.1257.
Griffiths, P.G., 1995, Initiation and frequency of debris flows in Grand Canyon, Arizona [M.S. thesis]: Tucson, University of Arizona, 52 p.
Griffiths, P.G., Webb, R.H., and Melis, T.S., 2004, Initiation and frequency of debris flows in Grand Canyon, Arizona: Journal of Geophysical Research, Surface Processes, v. 109, 14 p., F04002, doi:10.1029/2003JF000077.
Haan, C.T., 1977, Statistical methods in hydrology: Iowa State University Press, 378 p.
Hammack, L., and Wohl, E., 1996, Debris-fan formation and rapid modification at Warm Springs Rapid, Yampa River, Colorado: The Journal of Geology, v. 104, p. 729–740.
Hampton, M.A., 1975, Competence of fine-grained debris flows: Journal of Sedimentary Petrology, v. 45, p. 834–844.
Hanks, T.C., Lucchitta, I., Davis, S.W., Davis, M.E., Finkel, R.C., Lefton, S.A., and Garvin, C.D., 2002, The Colorado River and the age of Glen Canyon, *in* Young, R.A., and Spamer, E.E., eds., Colorado River, Origin and evolution: Grand Canyon, Arizona, Grand Canyon Association, p. 129–133.
Hereford, R., and Huntoon, P.W., 1990, Rock movement and mass wastage in the Grand Canyon, *in* Beus, S.S., and Morales, M., eds., Grand Canyon geology: New York, Oxford University Press, p. 443–459.
Hereford, R., and Webb, R.H., 1992, Historic variation in warm-season rainfall on the Colorado Plateau, U.S.A: Climatic Change, v. 22, p. 239–256, doi: 10.1007/BF00143030.
Hereford, R., Thompson, K.S., and Burke, K.J., 1998, Numerical ages of Holocene tributary debris fans inferred from dissolution pitting on carbonate boulders in the Grand Canyon of Arizona: Quaternary Research, v. 50, p. 139–147, doi: 10.1006/qres.1998.1987.
Hereford, R., Webb, R.H., and Graham, S., 2002, Precipitation history of the Colorado Plateau region, 1900–2000: U.S. Geological Survey Fact Sheet 119-02, 4 p.
Hintze, L.F., 1988, Geologic history of Utah: Provo, Brigham Young University, 202 p.
Hunt, C.B., 1967, Physiography of the United States: San Francisco, W.H. Freeman, 480 p.
Iverson, R.M., 1997, The physics of debris flows: Reviews of Geophysics, v. 35, p. 245–296, doi: 10.1029/97RG00426.
Iverson, R.M., Reid, M.E., and LaHusen, R.G., 1997, Debris-flow mobilization from landslides: Annual Review of Earth and Planetary Sciences, v. 25, p. 85–138, doi: 10.1146/annurev.earth.25.1.85.
Jibson, R.W., and Harp, E.L., 1996, The Springdale, Utah, landslide: An extraordinary event: Environmental and Engineering Geoscience, v. 2, p. 137–150.
Larsen, I.J., 2003, From the rim to the river: The geomorphology of debris flows in the Green River Canyons of Dinosaur National Monument, Colorado and Utah [M.S. thesis]: Logan, Utah State University, 195 p.
Larsen, I.J., Schmidt, J.C., and Martin, J.A., 2004, Debris-fan reworking during low-magnitude floods in the Green River canyons of the eastern Uinta Mountain, Colorado and Utah: Geology, v. 32, p. 309–312, doi: 10.1130/G20235.1.
McCune, B., and Grace, J.B., 2002, Analysis of ecological communities: Gleneden Beach, Oregon, MjM Software Design, 300 p.
Melis, T.S., Webb, R.H., Griffiths, P.G., and Wise, T.J., 1994, Magnitude and frequency data for historic debris flows in Grand Canyon National Park and vicinity, Arizona: U.S. Geological Survey Water Resources Investigations Report 94-4214, 285 p.
Pierson, T.C., and Costa, J.E., 1987, A rheologic classification of subaerial sediment-water flows, *in* Costa, J.E., and Wieczorek, G.F., eds., Debris flows/avalanches—Process, recognition, and mitigation: Reviews in Engineering Geology, v. 7, p. 1–12.
Radbrunch-Hall, D.H., Colton, R.B., Davis, W.D., Skipp, B.A., Lucchitta, I., and Varnes, D.J., 1976, Preliminary landslide overview map of the conterminous United States: U.S. Geological Survey Miscellaneous Field Studies Map MF-771, 1 sheet, scale 1:7,500,000.
Rudd, L.P., 2005, Using AVIRIS hyperspectral imagery to study the role of clay mineralogy in Colorado Plateau debris-flow initiation [Ph.D. thesis]: Tucson, University of Arizona, 248 p.
Schroder, J.F., 1971, Landslides of Utah: Utah Geological and Mineralogical Survey Bulletin 90, 51 p.
Starkey, H.C., Blackmoun, P.D., and Hauff, P.L., 1984, The routine mineralogical analysis of clay-bearing samples: U.S. Geological Survey Bulletin 1563, 32 p.
Stokes, W.L., 1988, Geology of Utah: Salt Lake City, Utah Museum of Natural History, 208 p.
Webb, R.H., Pringle, P.T., Reneau, S.L., and Rink, G.R., 1988, The 1984 Monument Creek debris flow: Implications for the formation of rapids on the Colorado River in Grand Canyon National Park: Geology, v. 16, p. 50–54, doi: 10.1130/0091-7613(1988)016<0050:MCDFIF>2.3.CO;2.
Webb, R.H., Pringle, P.T., and Rink, G.R., 1989, Debris flows in tributaries of the Colorado River in Grand Canyon National Park, Arizona: U.S. Geological Survey Professional Paper 1492, 39 p.
Webb, R.H., Melis, T.S., Griffiths, P.G., Elliott, J.G., Cerling, T.E., Poreda, R.J., Wise, T.W., and Pizzuto, J.E., 1999, Lava Falls Rapid in Grand Canyon: Effects of late Holocene debris flows on the Colorado River: U.S. Geological Survey Professional Paper 1591, 91 p.
Webb, R.H., Griffiths, P.G., Melis, T.S., and Hartley, D.R., 2000, Sediment delivery by ungaged tributaries of the Colorado River in Grand Canyon, Arizona: U.S. Geological Survey Water-Resources Investigations Report 00-4055, 67 p.
Webb, R.H., Belnap, J., and Weisheit, J., 2004, Cataract Canyon: A human and environmental history of the rivers in Canyonlands: Salt Lake City, University of Utah Press, 268 p.
Wells, W.G., II, Wohlgemuth, P.M., Campbell, A.G., and Weirich, F.H., 1987, Postfire sediment movement by debris flows in the Santa Ynez Mountains, California, *in* Erosion and sedimentation in the Pacific Rim: Proceedings of the Corvallis Symposium, International Association of Hydrologic Sciences Publication no. 165, p. 275–276.
Whipple, K.X., and Dunne, T., 1992, The influence of debris-flow rheology on fan morphology, Owens Valley, California: Geological Society of America Bulletin, v. 104, p. 887–900, doi: 10.1130/0016-7606(1992)104<0887:TIODFR>2.3.CO;2.
Williams, V.S., 1984, Pedimentation versus debris-flow origin of plateau-side desert terraces in southern Utah: The Journal of Geology, v. 92, p. 457–468.
Woolley, R.R., 1946, Cloudburst floods in Utah, 1850–1938: U.S. Geological Survey Water-Supply Paper 994, 128 p.

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